Three-dimensional ionospheric electron density structure of the Weddell Sea Anomaly


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This paper provides the first three-dimensional description of the ionospheric density structure of the Weddell Sea Anomaly (WSA). The WSA is characterized by a nighttime ionospheric density greater than that in daytime in the Weddell Sea region around the Antarctic Peninsula during the southern hemisphere summer. It was first observed by ground-based ionosondes located in the Antarctica back in the 1950s and was further investigated by two-dimensional maps over the oceans using TEC measurements collected by the TOPEX/Poseidon recently. Although these TEC maps have provided two-dimensional views for tracking the time-evolution and spatial coverage of the WSA, the vertical distribution of this peculiar feature is still unavailable. With the vertical ionospheric density profiles observed by the FORMOSAT-3/COSMIC, three-dimensional density structure of the WSA is presented here for the first time. Meanwhile, a similar WSA signature is observed in the northern and eastern hemisphere during June solstice by both the GPS-TEC and the FORMOSAT-3/COSMIC electron density observations. From the observed altitudinal structure of the WSA during 1800–2400 LT and the similar feature occurred in the opposite hemisphere suggest that the southward offset of the magnetic equator with respect to the geographic equator plays a major role for the WSA formation.

latitude of the Weddell Sea area is around $-50^\circ \sim -60^\circ$ N, close to $45^\circ$ dip angle where the wind driven plasma drift is the strongest [cf. Kohl and King, 1967; Rishbeth and Garriott, 1969]. Therefore, the equatorward neutral wind can still uplift the plasma to higher altitude effectively there in the evening (or, in other words, prevent the plasma from diffusing downward). On the other hand, the depleted ionospheric feature of the WSA during daytime is thought to be due to the daytime neutral winds blowing from equator to polar regions. The daytime poleward neutral wind accelerates the downward diffusion of the plasma along magnetic field lines and moves the $F$ region ionization to lower altitudes where recombination is much faster. The anomaly is most significantly seen in the Weddell Sea region, where greater magnetic declination angle and displacements between the magnetic and geographic equators occur.

Meanwhile, the global scale coverage of the two-dimensional WSA TEC map seen by TOPEX/Poseidon also shows that the WSA may be related to the southern equatorial ionization anomaly (EIA) crest [Horvath and Essex, 2003]. The source of ionization enhancement may also come from southward/poleward movement of the southern EIA crest at the West American sector where the magnetic equators are generally offset southward. Other possible explanations include weaker magnetic field of the region, change of the $[O]/[N_2]$ ratio, antisunward winds associated with high-latitude convection, and downward diffusion of the plasmaspheric ionization. Burns et al. [2008] found that there was a strong connection between the WSA and the behavior of the equatorial anomaly at dusk and that there was a continuity of this connection with the equatorial anomaly over Indonesia. They considered a number of possible mechanisms based on past literatures. To date, the relative importance for each of these possible mechanisms is not yet identified. The main purpose of this paper is to help identify possible WSA formation mechanisms through a detailed study of the three-dimensional density structure of the WAS that is observed by the FORMOSAT-3/COSMIC.

2. The FORMOSAT-3/COSMIC

The three-dimensional maps presented in this paper are obtained from the radio occultation [cf. Schreiner et al., 1999] experiment of the Formosa Satellite 3 and Constellation Observing System for Meteorology, Ionosphere, and Climate (FORMOSAT-3/COSMIC or F3/C in short). The constellation was launched into a circular low-Earth orbit at 0140 UTC on 15 April 2006 and had collected more than a million ionospheric electron density profiles around globe. Some initial validation works of the F/C radio occultation observations have been carried out by Schreiner et al. [2007] and Lei et al. [2007]. These validation works have shown high quality of the $F$ and good correlations between the $F$ observed electron density profiles and those observed by radars. The six microsatellites are close to each other at the initial parking orbit at a $72^\circ$ inclination angle orbital plane with an altitude of around 500 km after launch. The constellation has now deployed to its final mission orbit, having $30^\circ$ separation in longitude between each of microsatellites at around 750–850 km altitude. In this paper, observations in 2007 are used to construct monthly ionospheric maps. Some satellites were still in the orbital lifting process and the microsatellites were at different altitudes; therefore we only present ionospheric maps between 200 and 500 km altitude. The three-dimensional electron density maps presented here are produced by averaging 1 month of observations, similar to the process that was described by Lin et al. [2007].

3. Results and Discussions

Figure 1 shows the electron density for various altitude and longitude slices, together with the total electron content integrated between 100 and 500 km altitudes in the bottom slice. The white solid lines in Figure 1 indicate the magnetic equator calculated from the magnetic quasi-dipole coordinates [Richmond, 1995] which use a realistic geomagnetic field model of International Geomagnetic Reference Field. The WSA and the nearby density enhancement region in the southern hemisphere occur over a large area between $-30^\circ \sim -90^\circ$ N latitudes and $-150^\circ \sim -30^\circ$ E longitudes. The WSA feature is most significantly seen at an altitude of 300 km as shown in Figure 1. Meanwhile, similar density enhancement also extends to the east of the Weddell Sea, between $-60^\circ$ and $-30^\circ$ E longitude. To examine the time evolution of the WSA formation, we further show the electron density slices at $-90^\circ$ E longitude. The magnetic equator is located at around $-11^\circ$ N geographic latitude at this longitude. These data are plotted for local times from 1800 to 2400 LT in 2 h increments in Figure 2. The southern EIA crest is much stronger than the northern crest at 1800 LT as shown in Figure 2, which is consistent with the results of Lin et al. [2007], who showed that the EIA crest in the summer hemisphere lasts much longer than that in the winter hemisphere. At a later local time, 2200 LT, the region of enhanced electron density located between $0^\circ$ and $-30^\circ$ N shows a significant decrease, while increased electron densities are seen between $-30^\circ$ and $-60^\circ$ N. Additionally, the ionospheric layers in the southern hemisphere show tendency of uplift after 2000 LT, especially at latitudes between $-30^\circ$ and $-60^\circ$ N around 250 km altitude (Figure 2). The uplift becomes weaker at 2400 LT and the electron density enhancement region moved southward. To compare the difference between the Weddell Sea region and other sectors where the magnetic equator is offset at the northern geographic hemisphere, Figure 3 shows similar plots to Figure 2 but for $30^\circ$ E longitude instead (the magnetic equator located at around $9.5^\circ$ N geographic latitude at this longitude). The feature of the WSA is not seen in the Figure 3, only some electron density increases are seen at lower altitudes between $-75^\circ$ and $-90^\circ$ N after 2000 LT, which may possibly result from remaining solar photoionization or high-latitude particle precipitations. Although a stronger southern EIA crest remains in Figure 3, spanned around $15^\circ \sim 30^\circ$ N latitudes, electron density between $-30^\circ$ and $-60^\circ$ N is much smaller in $30^\circ$ E longitude than that in the $-90^\circ$ E sector. Therefore, the layer uplifts shown around 250 km altitude after 1800 LT in Figure 3 do not help accumulating more electron density to form the density enhancement region between $-30^\circ$ and $-60^\circ$ N as those shown in Figure 2. From both Figures 2 and 3, the ionospheric layers in both longitude sectors are uplifted to
Figure 1. Electron density slices at various altitudes and longitudes at 2400 LT in December 2007. The total electron content integrated between 100 and 500 km altitude is also shown at the bottom slice. The labeled longitudes and latitudes are in geographic coordinate while the white line indicates the magnetic equator calculated from the magnetic quasi-dipole coordinates.
higher altitudes after 1800 LT indicating that the equatorward neutral winds exist in both longitudes. The stronger uplift shown in −90°E longitude suggests that the equatorward component of the neutral wind is stronger there than at 30°E. This difference is consistent with the neutral wind patterns shown by Kil et al. [2006], that the parallel-to-magnetic field line (or field-aligned hereinafter) component of the neutral wind shows a stronger equatorward magnitude at −90°E than at 30°E. It may be due to the fact that the magnetic field lines are declined eastward most significantly in the −90°E longitude sector. The nighttime neutral wind tends to move eastward at F layer height (see the HWM 93 results at 2200 LT shown in the work of Kil et al. [2006]) and the eastward wind contributes an additional

**Figure 2.** Two-dimensional electron density slices at −90°E geographic longitude from 1800 to 2400 LT in December 2007.

**Figure 3.** Two-dimensional electron density slices at 30°E geographic longitude from 1800 to 2400 LT in December 2007.
Figure 4. Electron density slices at various altitudes and longitudes at 2200 LT in June 2007. The total electron content integrated between 100 and 500 km altitude is also shown at the bottom slice. The labeled longitudes and latitudes are in geographic coordinate while the white line indicates the magnetic equator calculated from the magnetic quasi-dipole coordinates.
northward/equatorward field-aligned component due to the eastward declination. On the other hand, the magnetic declination at 30°E is much smaller and the zonal wind contributes insignificantly to the meridional component. The higher electron density between −30 and −60°N (part of the southern EIA crest) and the stronger equatorward winds result in the WSA feature in −90°E longitude sector. Therefore, the southward offset of the magnetic equator and the eastward magnetic declination in the Weddell Sea region may be the major reasons for producing this anomalous feature. The southward offset of the magnetic equator makes the southern EIA crest move closer to the Weddell Sea region, and the ionospheric layers in the region are later uplifted to higher altitudes by stronger equatorward winds. It is worth to note that in addition to southward excursion of the EIA crest and the wind-produced uplift, the ionization comes from nighttime downward diffusion of the plasma from topside ionosphere or plasmasphere [e.g., Burns et al., 2008] and the photoionization due to later sunset time at the Weddell Sea region may also contribute to the enhancement by providing fresh plasma. It is noted that the additional plasma coming from topside ionosphere and photoionization may also occur in 30°E longitude. However, larger dip angle and weaker equatorward wind in 30°E longitude result in a faster downward diffusion of the fresh plasma to lower altitude and less plasma accumulation. Therefore, the enhancement is not seen in that longitude sector.

From Figures 1 to 3 and possible processes described above, the formation of the Weddell Sea Anomaly is likely due to the offset of the magnetic and geographic equators with some additional effects due to magnetic declination. If the physical processes result from the offset of the equators are the major mechanism, features similar to the Weddell Sea Anomaly should also be seen in the opposite hemisphere during northern hemisphere summer. Figure 4 shows the three-dimensional electron density slices at 2200 LT during June 2007. A feature similar to the WSA is most clearly seen at 40°~60°N geographic latitude around 120°E~140°E geographic longitude. This northern summer feature is also seen by global ionospheric maps (GIMs) at similar local time constructed by continuous ground-based GPS TEC observations by Center for Orbit Determination in Europe (CODE) at Astronomisches Institut Universität Bern (AIUB), Switzerland [Schaer, 1999]. To compare with the F3/C results and the longitudinal variation, the GPS TEC retrieved from the GIMs are reconstructed in constant local time maps in Figure 5. It is noted that the GIMs are only available in every 2-h interval from the open data access and therefore the constructed constant local time map show striped shape along longitudes. The feature of the anomalous electron density enhancement shown in the northern and eastern hemisphere around June solstice is seen very similarly from both the F3/C and GPS TEC observations (Figures 4 and 5). The similar to WSA ionospheric structure, an enhanced ionospheric layer in the magnetic midlatitude region being uplifted during evening hours, is also seen in a wide range of longitudes between 0°E and 180°E where the magnetic equator is offset into the northern geographic hemisphere. This implies that the formation of both this feature and the WSA is strongly

Figure 5. Global constant local time maps of the GPS-TEC composed from the global ionospheric map (GIM) at 1500, 2000, 2100, and 2200 LT on 1 July (DOY:182) 2007. Signatures of the similar-to-WSA structure are indicated by red circles.
connected to the offset of the magnetic and geographic equators. The major difference is that the feature in the northeast hemisphere lasts shorter than that in Weddell Sea region. This difference may be due to the larger magnetic field declination in Weddell Sea region. The eastward declination of the magnetic field lines in the Weddell Sea region provides an additional northward/equatorward field-aligned wind component projected from the nighttime eastward winds at F layer height. The stronger equatorward wind in the Weddell Sea area keeps the ionospheric layers at higher altitudes for longer time, so that the ionization enhancement lasts longer.

Additionally, downward diffusion of the plasmaspheric plasma may also contribute to the plasma enhancement in the Weddell Sea region, since the WSA is located in the equatorward edge of the midlatitude trough [cf. Burns et al., 2008]. This effect cannot be identified from electron density observations presented here. Plasma drift observations on board satellites, such as DMSP, may be helpful to clarify this effect.

4. Summary

This paper presents the first three-dimensional electron density structure of the Weddell Sea Anomaly (WSA) by radio occultation observation of the FORMOSAT-3/COSMIC. It is shown that the WSA spanning in a large area in the southern hemisphere and most significantly seen around 300 km altitude. Comparing the vertical structure of ionospheric electron density at WSA longitude (Figure 2) with other longitude without this anomalous feature (Figure 3), the southward offset of the magnetic equator from the geographical one and the larger easterly magnetic declination at the Weddell Sea region seem to play major roles in producing this middle- to high-latitude density enhancement at F region. The southward offset of the magnetic equator results in a larger northward/equatorward neutral wind which sustains the ionospheric layer at higher altitudes. Meanwhile, the similar WSA seen in the opposite hemisphere (northeast hemisphere) at the June solstice (northern hemisphere summer) suggests again that the offset between magnetic and geographic equators may be the underpinning feature that leads to the formation of the WSA. The three-dimensional electron density structure of the WSA observed by FORMOSAT-3/COSMIC provides important hints for future modeling work.

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References


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